NASA
Capability Road Map (CRM) 4
Advanced Telescope and Observatory (ATO)

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4 Advanced Telescope and Observatory

4.1 General Capability Overview

4.1.1 Capability Description

The Advanced Telescopes and Observatories (ATO) capability roadmap includes technologies necessary to enable future space telescopes and observatories collecting all electromagnetic bands, ranging from x-rays to millimeter waves, and including gravity-waves. It has derived capability priorities from the current and developing Science Mission Directorate (SMD) strategic roadmaps and, where appropriate, has ensured their consistency with other NASA strategic and capability roadmaps. The team collaborated closely with the Scientific Instruments and Sensors Roadmap team, which had the responsibility to address technologies associated with the detection, conversion, and processing of observed signals into data.

In cooperation with the necessary science instruments, future space telescope technologies provide key enabling capabilities for four strategic roadmap (SR) areas:

- Searches for Earth-like planets and habitable environments around other stars. (SR4)
- Exploration of the universe to understand its origin, structure, evolution, and destiny. (SR8)
- Earth Science (SR9)
- Sun-Solar System Science (SR10)

In addition, Advanced Telescope and Observatory technology developed for NASA is synergistic with the needs of and technology developments within several other government agencies ranging from DoD and the NRO to DoE. This roadmap has been developed with full participation of representatives from those agencies and appropriate synergisms, partnerships, and leveraging opportunities have been identified.

The transition from the current set of on-orbit great observatories to the future suite of Advanced Telescopes and Observatories is shown in Figure 4.1. The Hubble Space Telescope (HST), Spitzer Space Telescope and Chandra X-ray Telescope are operational observatories and represent the state-of-the-art in advanced telescopes. The James Webb Space Telescope (JWST) and Space Interferometer Mission (SIM), scheduled to launch in the next decade, require new technologies in lightweight optics, wavefront sensing and control, and precision metrology. Follow-on missions, such as the Terrestrial Planet Finder Coronagraph (TPF C), Constellation-X (Con X), and Single Aperture Far-Infrared telescope (SAFIR), require further advanced capabilities in mirror technology, wavefront sensing and control, and cryogenic thermal control systems in a logical sequence. Longer-term missions require formation flying and more advanced imaging techniques (interferometric in some cases) to increase their effective aperture size.

As shown in Figure 4.2, the vantage points for future observatories depend on the desired science. In the cases of Exploration of the Universe and the Search for Earth-like Planets, the overwhelmingly favorite vantage point is the Sun-Earth Lagrange Point L2 (the current location of WMAP[1] and planned orbit for JWST). L2 provides a stable thermal environment, simple operational scenarios for communications and attitude correction, and a large unobscured view of the universe. Some, but not all of these advantages are provided by heliocentric drift-away orbits, but there is ample room at L2 for a large number of missions.

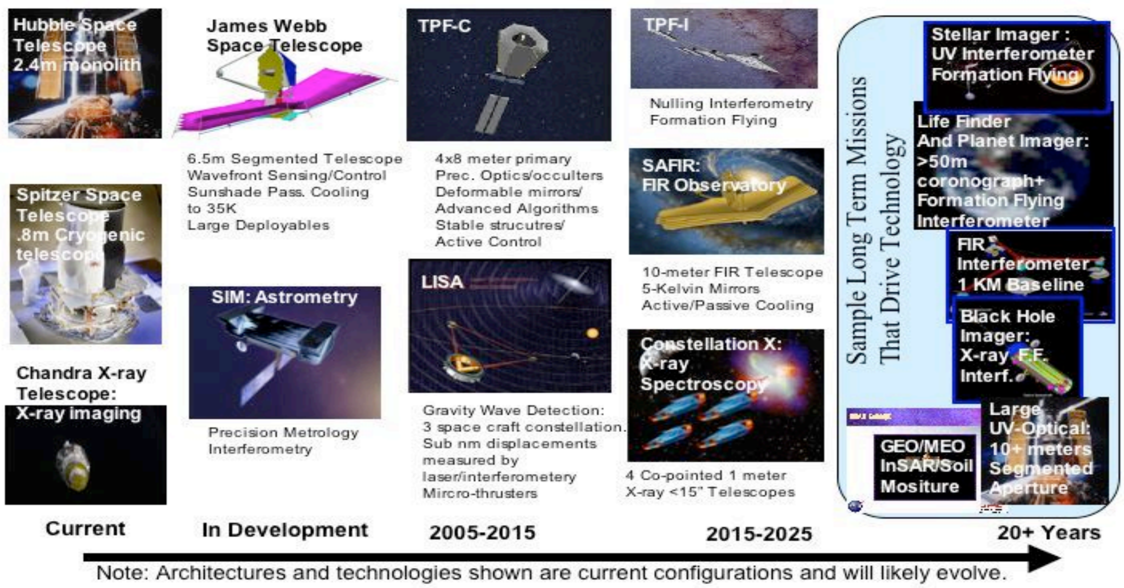


Figure 4.1: The transition from the current set of operating Great Observatories to the future suite of Advanced Telescopes and Observatories.

[1] Wilkinson Microwave Anisotropy Probe.

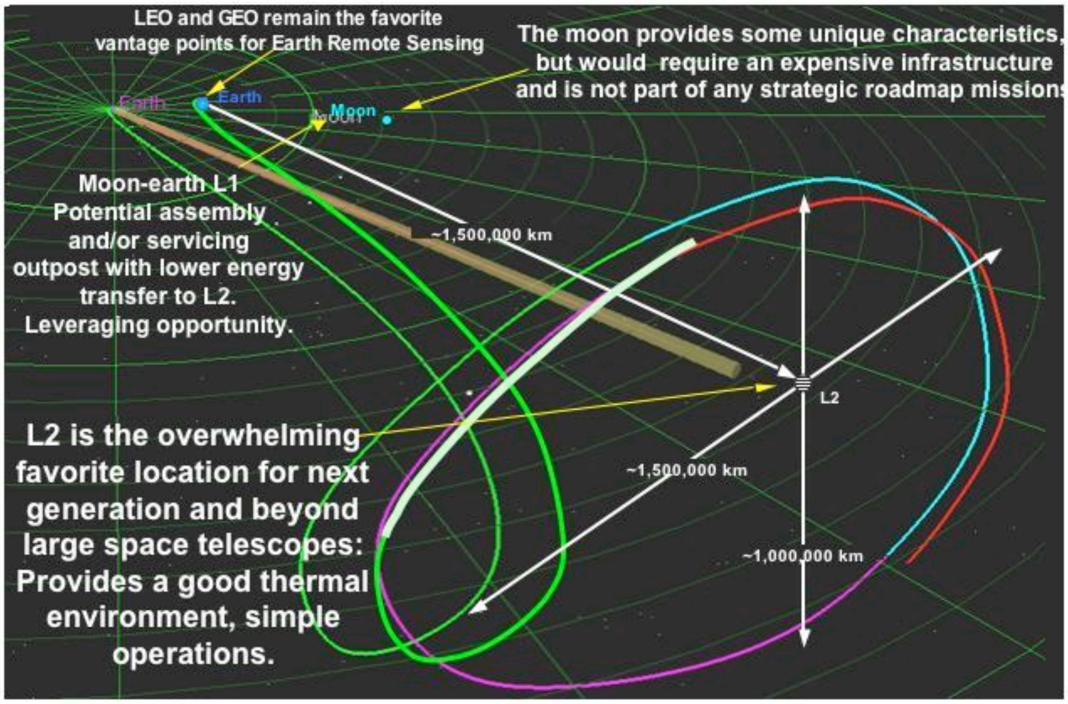


Figure 4.2: Locations for future space facilities depends upon planned activities: Sun-Earth L2 for next generation space observatories, Moon-Earth L1 for potential servicing, assembly, and transfer, and LEO/GEO for Earth science and applications.

Because of the large number of advanced missions slated to be located at L2, the ATO roadmap highlights servicing of missions destined for L2 as a long-term strategic goal that could be synergistic with aspects of the human Moon-Mars exploration program. Moreover, extremely large apertures needed for ultimately imaging Earth-size planets in detail will be so large that they may require not only servicing, but also assembly. Putting a telescope on the moon would require designing systems that can survive landing loads, more complex operations, a generally less desirable thermal environment, consideration of dust, and accessibility considerations. The moon does offer a gravity field that can be useful for large liquid mirrors and also opportunities to leverage flights for other exploration purposes. A better leveraging option might be an outpost at the Earth-Moon L1 Lagrange point that has very low energy transfer to the Sun-Earth L2 and could permit leveraging flights made to the moon for other purposes.

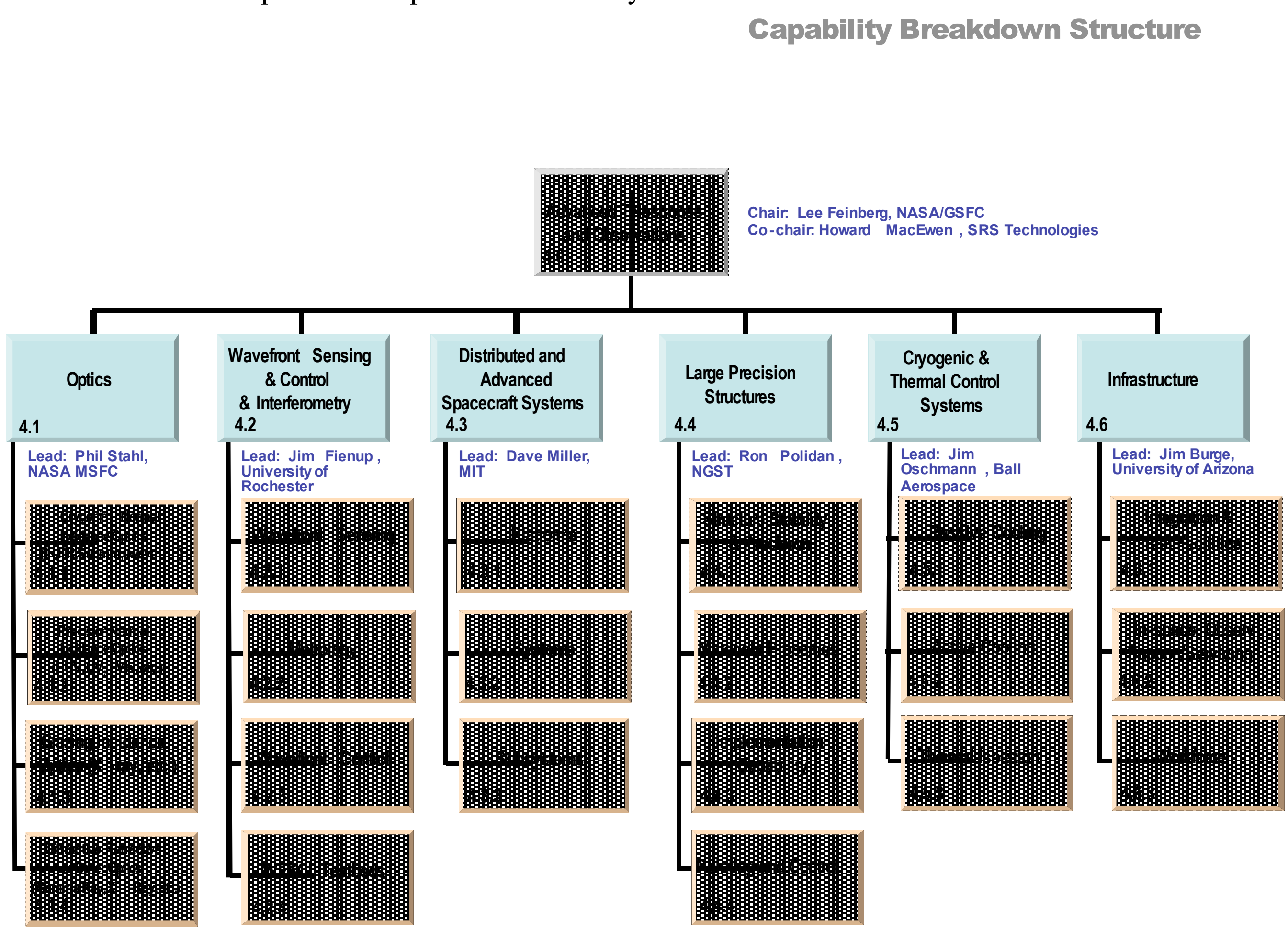
Although astronomy missions heavily favor L2 as a vantage point, Earth science and monitoring missions and Sun-Earth missions still overwhelmingly favor Earth orbits (LEO and GEO)[2]. A

[2] The Sun-Earth L1 point is useful for some solar monitoring purposes.

priority for many of these missions is increased aperture at reduced cost, as well as affordability of multiple identical spacecraft. These capabilities are outlined in more detail below and are, in many cases, synergistic with some of the needs of other government agencies.

4.1.2 Capability Breakdown Structure

The capabilities and technologies that comprise this roadmap are summarized in the Capability Breakdown Structure (CBS) shown in Figure 4.3. As can be seen, the roadmap consists of six basic areas, each of which is further broken down into sub-capabilities. The key area of optics is addressed first and is organized principally by wavelength. Another critical area for many future missions is Wavefront Sensing and Control (including interferometry and testbeds). The third area, Distributed[3] and Advanced Spacecraft Systems (DASS), becomes increasingly important in the longer term, as the requirement for aperture size exceeds the limits of a single mechanical structure. Large Precision Structures and Cryogenic and Thermal Control Systems will also providing enabling technologies for many future systems. Finally, it is essential to address infrastructures (both ground and space) because of the extremely broad, critical impact they will have on future space telescope and observatory architectures.



[3] I.e., formation flown spacecraft.

Figure 4.3 – Capability Breakdown Structure

4.1.3 Benefits

Development of these capabilities is necessary to enable systems for Earth science and applications and astronomical observatories. In turn, these future facilities will achieve the priority goals identified in the *Vision for Space Exploration* and numerous National Academy of Sciences decadal reviews and recommendations. In addition, like their predecessors such as HST, many of the observations that they will provide will be completely unexpected.

4.1.4 Key Architecture / Strategic Decisions

The critical decisions that NASA needs to make that will most greatly impact future telescopes and observatories are summarized in Table 4.1 below:

Table 4.1 – Key Decisions

Key Architecture/ Strategic Decisions	Date Decision is Needed	Impact of Decision on Capability
Decision to jointly invest with other agencies in major large optics technology capabilities	2006/2007	Allows leveraging of available funding to develop new technologies: e.g., replicated optics, active wavefront sensing and control systems, and low cost 3-meter class telescopes. Could enable future Earth and other science missions at lower cost and also help serve national security interests. Builds upon the heritage of joint investments among NASA, NRO and AFRL on lightweight mirror technology for JWST and other applications.
NASA decision to work with other government agencies to build/modify large optics test facilities for multiple missions	2008 (TPF-C)	System level ground tests are expensive and complex. JWST is stressing the limits of available facilities. NASA needs to decide whether to leverage the JWST test facility for future missions (TPFC, SAFIR) or to build a new facility that can also serve other national interests.
NASA decision to fund new heavy lift launch vehicle, which enables larger space observatories	20072008 (TPF-C)	Larger shrouds and/or lower cost/mass launch vehicles could enable larger apertures (and potentially heavier instruments with greater capabilities).
Decision to sustain and expand NASA's on-orbit assembly and servicing capability to achieve multiple priority objectives,	Libration mission servicing: 2010 (SAFIR),	Enables extended lifetime missions with greater performance and lower risk. Common systems provide resources for on-orbit assembly, repair, servicing, and

including large optical systems	Libration mission assembly: 2015 (LF)	may be a capability for sustaining space operations experience. Assembled systems enable larger size and mass telescopes. Need to make decision early enough to affect observatory architecture. SAFIR is initial candidate for servicing. LF is candidate for assembly.

4.1.5 Major Technical Challenges

The major technical challenges are shown in Table 4.2. These challenges are included in this roadmap because they enable critical missions or provide a generic capability that can enable multiple missions. The sequence of challenges in the Table is based upon both NASA's strategic needs and the technical difficulty of each challenge (and the attendant need to build upon prior developments). Optics and wavefront sensing and control are critical to enabling new types of science and are the most critical telescope technologies needed for nearer term missions[4]. On the other hand, precision formation flying is a very difficult technology, but it will enable multiple longer-term missions. Other technologies such as coolers and large structures are key to enabling cost effective architectures and are generally enhancing in all time frames. Challenges in the area of infrastructure were identified because of their critical importance in making missions cost-effective or programmatically viable. Finally, underlying all of these specific challenges is the great generic challenge: mission affordability.

Table 4.2 – Major Technical Challenges

2006-2010
Very Large Precision Mirrors for TPF-C 4 x 8 meter monolithic mirror (< \$2 M/m^2 and < 50 kg/m^2) Extremely low mid-spatial frequency surface figure errors (4 nm rms) Coating reflectance and polarization uniformity Precision metrology for qualifying mirror specifications
Low-Cost Large-Aperture, Lightweight Grazing Incidence Mirrors for Con-X 1.6 x 1 meter segments, 15 arc second resolution, < \$0.1M/m^2, <3 kg/m^2 Manufacturing technology – replication, etc. Mirror substrate materials – thermal stability, areal density, stiffness, etc.
High-temporal-bandwidth wave front sensing and control (WSFC) for real-time active control of segmented telescopes Large UV/ Optical Telescope (LUVO) 3-meter-class low-cost telescopes
High contrast speckle-reduction algorithms 10^{10} broadband contrast for TPF-C Could include active WFSC and improved occulters
Formation Flight Technology Demonstrations Roughly 3/4 of long-term proposed Earth and space science missions emphasized

[4] But note that parallel development of new sensors and detectors is equally critical for these science missions.

distributed and formation flight architectures Need a sequence of flight tests to mature these technologies in a cost-effective manner.
Low-Cost 3-meter Class Mirrors Manufacturing technology – low-cost replication enables Earth, solar, astronomy missions Mirror Substrate Materials – thermal stability, areal density, stiffness, etc. Cryogenic mirrors for SAFIR (200 nm rms, < $0.5 M/m^2 and < 25kg/m^2) Precision Mirrors for LUVO (5 nm rms, < $2 M/m^2 and < 25kg/m^2) RPF-I, IP, LF and BBO.
2010 – 2020
Replicated Spacecraft and Formation Control. Multi-spacecraft formations are expensive Propellant consumption places strict limitations on lifetime options
Active/Passive Cooled Optical Systems Passive cooling techniques (like sunshields) Active coolers Achieve 4-10K cooling across large mirror surface areas
Integration and test paradigm shift Current: system assembly and test on the ground Future: final system deployment and verification in space Requires a new level of confidence in software modeling and alternative architectures
On-orbit servicing and assembly capabilities Human servicing and assembly In-space robotics
Advanced spatial interferometric imaging including Wide field interferometric imaging Advanced nulling Will enable missions ranging from Stellar Imager to FIRSI to TPFI.
2020 and Beyond
Low-Cost Large-Aperture, Lightweight Grazing Incidence Mirrors for EUXO 8 meter segments, 0.1 arc second resolution, < $1 K/m^2, <0.5 kg/m^2
Many Spacecraft in Large Baseline Formations Complex real-time maneuver path planning and sensing and control Changed manufacturing and testing processes Large separations create synchronization, sensing and communications challenges.

4.1.6 <u>Key Capabilities and Status</u>

The timeline for the Advanced Telescope and Observatory Roadmap is shown in Figures 4.4a and 4.4b (or should this be figure 4.5?). This timeline lists strategic missions that require ATO capabilities across the top. Key capabilities that enable these missions are then shown with arrows pointing to the first mission supported. The capabilities are assumed to be required 5 years prior to a mission; that is, when the technology must be at TRL-6. These capabilities then align with key milestones and metrics that appear within the green banner at the time needed in the appropriate ATO sub-capability (e.g., optics). This provides a clear audit trail from missions to milestones in each of the essential technologies.

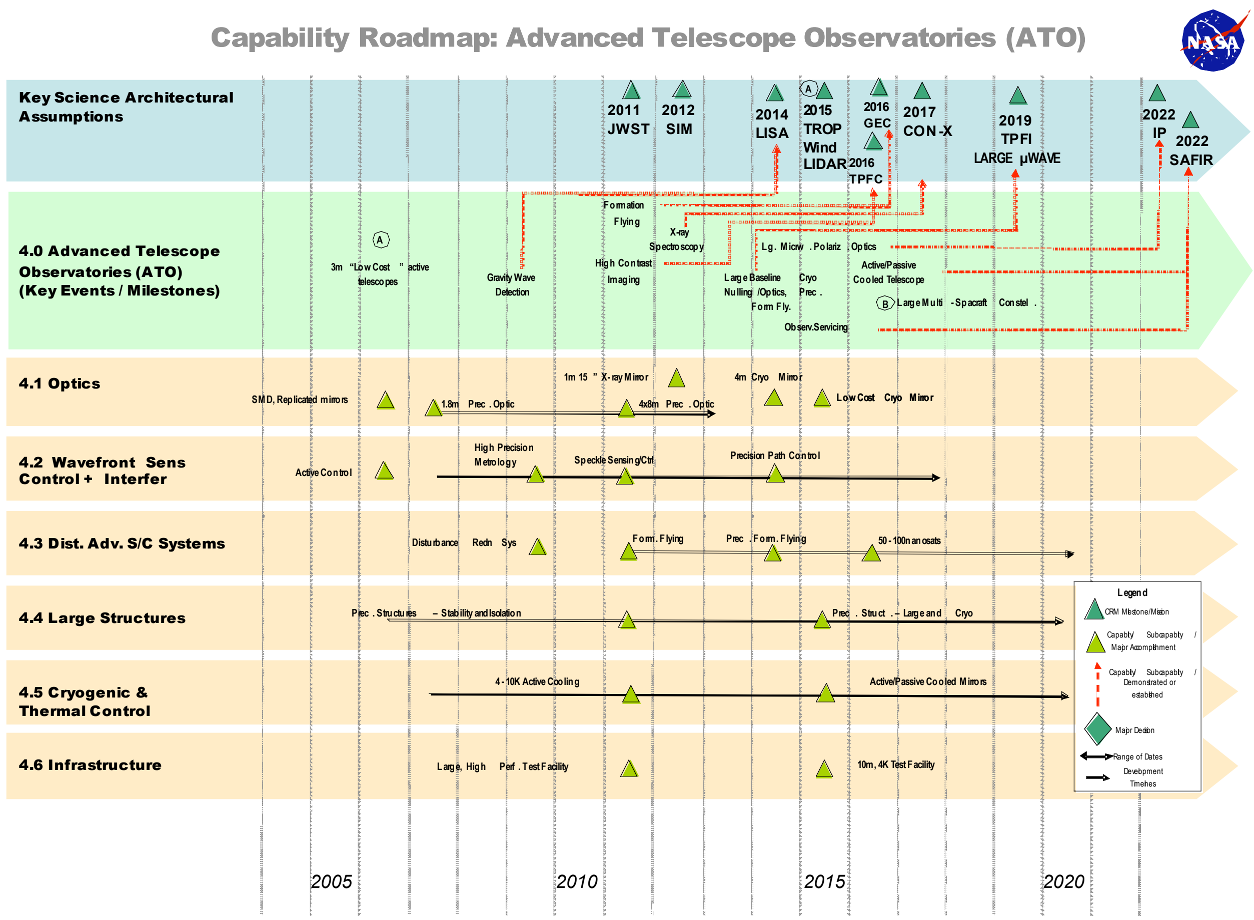
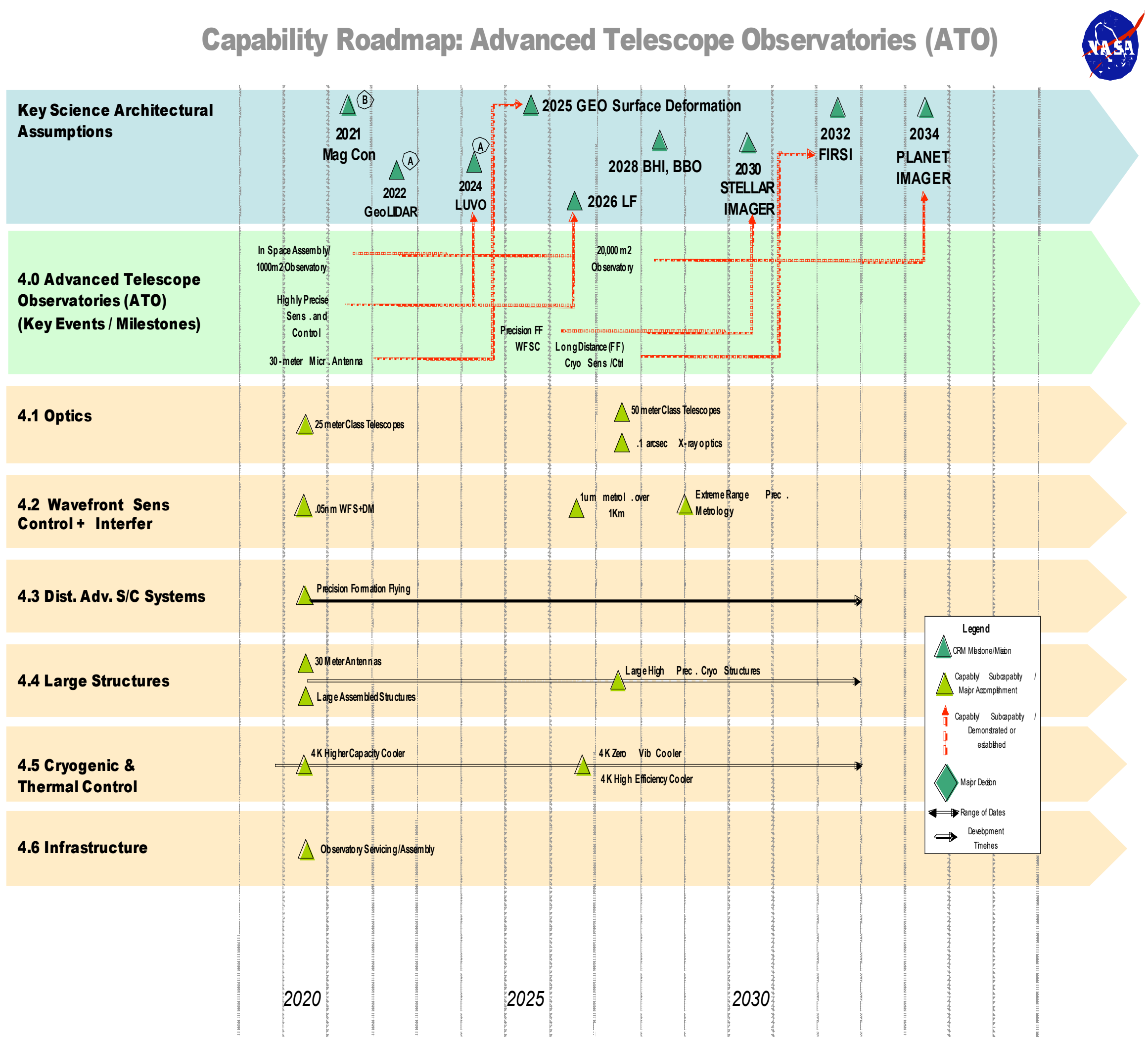


Figure 4.4. Advanced Telescope and Observatory Capability Roadmap Timeline

Figure 4.4b (or Figure 4.5)



4.1.6.1 Optics

In the past, optics development has primarily been driven by the technical challenge of making large-aperture, low-areal density mirrors of sufficient surface figure, precision, and mechanical stiffness. As the areal density of high optical quality mirrors reaches minimum attainable limits, programmatic factors such as cost and schedule for production are becoming increasingly dominant considerations. Thus, future optics will need to improve both the technical and programmatic performance of optics. The ultimate goal is to mass produce mirror segments for segmented telescopes, or 'classes' of telescopes - resulting in an improved cost/performance "Moore's Law" for space telescopes.

In looking at the specific needs of optics, we have grouped optics into four major categories of needs:

- Cryogenic Optics (for IR, Far-IR, Sub-MM, Microwave)
- Precision Optics (for EUV, FUV, UV, Visible)
- Grazing Incidence Optics (for X-Ray)
- Diffractive, Refractive & Novel Optics (for Gamma, X- ray or other)

Cryogenic Optics:

Future infrared/far-infrared/sub-millimeter and millimeter wavelength missions require large-aperture mirrors of modest optical quality that operate at temperatures from 4 to 40K. Current state of the art cryogenic mirrors can satisfy most of the technical requirements for such missions, but their areal cost is too great. The most important enabling capability is therefore to reduce the areal cost of cryogenic mirrors by an order of magnitude: approaches to achieve this goal include replication, nanolaminates, near-net shaping, casting, slumping, and advanced polishing techniques. Additionally, several specific future missions can be enabled by doubling or tripling the size of cryogenic mirrors while halving their areal density. Polarization preserving uniform optical coatings will also be required for cryogenic missions.

The current science roadmaps identify several potential cryogenic telescope missions including JWST, TPF-I (Terrestrial Planet Finder Interferometer), IP (Inflation Probe), SAFIR (Single Aperture Far-IR), LF (Life Finder) and PI (Planetary Imager). LF and PI may or may not be cryogenic. There are also several potential cryogenic Probe missions that are not included in the roadmaps. JWST defines the current state-of-the-art for cryogenic telescopes. It will employ a segmented primary mirror composed of eighteen 1.5 meter hexagonal segments where each segment has a surface figure of 20 nm rms, an areal density of less than 40 kg/m^2 and an areal cost of approximately $4M per square meter. In the near to mid-term, there are three planned cryogenic telescope missions: TPF-I, SAFIR and IP. In the far-term is the Far-IR Space Interferometer (FIRSI). A summary of the current and future cryogenic mirror requirements is provided in the tables below[5].

[5] Note that the requirements for some possible missions, such as LF and PI, are not well enough defined as yet to be included in the tables.

Table 4.3 Current Cryogenic Missions Requirements

Capability Metrics	Spitzer	AMSD	Herschel	SPICA	JWST	CMB-POL	Units
Primary Aperture	.85	1.4	3.5	3.5	6.5	4	meters
Segment Diameter	.85	1.4	3.5	3.5	1.3	2 to 4	meters
# of Telescopes	1	1	1	1	1	1	units
Total Area	.55	1.35	10	10	25	~ 12	m^2
Areal Cost	~ $10M	$4M	~ $2.5M	?	< $4M	~ $100K	$/$m^2$
Areal Density	~ 28	~ 20	~ 24	~ 30	< 50	~ 30	kg/m^2
Diffraction Limit	5.5	2	80	5	2	600	μm
RMS Surface Fig	75	77	3000	175	20	6000	nm
Mech Stability	?	> 100	?	?	> 200	> 200	Hz
Thermal Stability	~ 20	20	?	?	20	6000	nm
Phasing	NA	NA	NA	NA	10	3000	nm
Wavelength Range	3-180	NA	60-670	5-200	0.6-28	600-6000	μm
Operating Temperature	4	30	80	4.5	< 50	< 40	K

Table 4.4 Future Cryogenic Mission Requirements

Capability Metrics	JWST	CMB-POL	Origin Probe	SAFIR	SPIRIT	TPF-I	SPECS	FIR/SM Interfere	Units
Primary Aperture	6.5	4	1 to 3	10	1	4	4	25	meters
Segment Diameter	1.3	2 to 4	1 to 3	2	1	2 to 4	2 to 4	> 2	meters
# of Telescopes	1	1	1	1	2	4	3	3	units
Total Area	25	12	< 10	50	1.6	~ 50	~ 36	~ 1500	m^2
Areal Cost	< $4M	~ $100K	< $1M	~ $500K	< $1M	< $1M	< $1M	< $100K	$/$m^2$
Areal Density	< 40	~ 30	~30	< 25	~ 30	< 25	< 25	< 15	kg/m^2
Diffraction Limit	2	600	2	20	1	1	1	40	μm
RMS Surface Fig	20	6000	20	200	10	10	10	400	nm
Mech Stability	> 200	> 200	> 200	> 200	> 200	> 200	> 200	> 200	Hz
Thermal Stability	20	6000	20	200	10	10	10	400	nm
Phasing	10	3000	10	100	NA	5	5	200	nm
Wavelength Range	0.6-28	600-6000	0.3-5	10-1000	20-800	6 - 18	40-640	40-500	μm
Operating Temp	< 50	< 40	< 40	~ 4	~ 4	~ 40	~ 4	~ 4	K

Precision Optics:

Future extreme ultraviolet, ultraviolet and visible wavelength missions will require large-aperture, extremely smooth, and highly stable ambient temperature mirrors. The most challenging mission in the near term is TPF-C (Terrestrial Planet Finder Coronagraph). TPF-C requires a primary mirror that has never before been demonstrated on the ground let alone in space - an extremely smooth (4 nm rms surface) 4 by 8 meter lightweight (~40 kg/m^2) mirror with extremely uniform optical coating reflectivity and polarization properties. The cost-effective fabrication of such a mirror requires the application to an 8 meter class mirror of precision optical metrology techniques previously only demonstrated on < 0.5 meter class microlithography optics.

Because of launch vehicle limitations, some future missions may choose a segmented mirror. While it is easier to manufacture smaller mirror segments, a segmented mirror telescope operating in the UV/Visible has its own challenges. To minimize scattered light and diffraction effects, the segments must be accurately figured and polished completely to the mirror's physical edge. Additionally, each segment's position must be mechanically controlled to extreme tolerances (0.1 nm). Three specific enabling coating technologies are 80% reflectivity coatings from 90 to 120 nm, 0.1% uniform reflectivity and 0.1% uniform polarization coatings from 400 to 1000 nm, and improved dichroic, spectral and combiner coatings.

Precise wavefront control is also required to enable all planned large aperture UV/Visible missions. TPF-C requires advances in both passive and active techniques. Passive techniques include figuring and polishing secondary and primary mirrors to eliminate mid-spatial frequency surface errors in addition to maintaining reflectivity and polarization uniformity across the entire coating. Active techniques include speckle sensing and control with high-density deformable mirrors and/or active telescope mirrors. These technologies are covered in detail in the WFSC section below. A summary of current and future precision optics requirements is provided in the tables below.

Table 4.5 Current Precision Optics Missions Requirements

Capability Metrics	FUSE	HST	AMSD	SIM	LISA	JDEM	Origin Probe	DSN Com	Units
Primary Aperture	0.4	2.4	1.4	0.35	0.3	2.4	2 to 3	3	meters
Segment Diameter	0.4	2.4	1.4	0.35	0.3	2.4	TBD	TBD	meters
# of Telescopes	4	1	1	2	6	1	1	1	units
Total Area	.55	4.5	1.25	0.2	0.4	4.5	4 to 7	5	M^2
Areal Cost		$10M	$4M			<$3M	<$3M	< $2M	$\$/m^2$
Areal Density	54	180	~ 20			~ 40	~ 40	~ 30	kg/m^2
Diffraction Limit	500	500	550			1	< 500		nm
RMS Surface Fig	16	6.4	20						nm
Mech Stability			> 100						Hz
Thermal Stability			< 10						nm
Phasing	NA	NA	NA			NA	NA	?	nm
Wavelength Range	90-112 100-120	115-1000	NA			350-1700	90-1000		nm
Operating Temp	300	300	300	300	300	300	300	300	K

Table 4.6 Future Precision Optics Mission Requirements

Capability Metrics	JDEM	Origin Probe	DSN Com	MTRAP	Earth Sci	Large UVO	TPF-C	SI	BBO	LF	PI	Units
Primary Aperture	2.4	2 to 3	3	5		10	4 x 8	1	3	25	50	meters
Seg Diameter	2.4	TBD	TBD	~ 2		~ 2	TBD	1	TBD	TBD	TBD	meters
# of Telescope	1	1	1	1		1	1	30	6	10	10	units
Total Area	4.5	4 to 7	7	20		50	20	~ 25	~ 40	5000	20,000	m^2
Areal Cost	<$3M	<$3M	<$2M	<$2M		<$2M	<$2M	<$1M	<$1M	<$10K	<$2K	$\$/m^2$
Areal Density	~ 40	~ 40	~ 40	< 20		< 20	< 50	< 40	< 25	TBD	TBD	kg/m^2
Diffraction Limit	1	< 500		500 nm		500	500	150		800	600	nm
RMS Surf Fig				15		5	4	5				nm
Mech Stability							< 0.2 nm					Hz
Thermal Stable							< 0.2	0.5				nm
Phasing	NA	NA	?	NA			< 0.2	5			0.05	nm

Wavelength Range	350-1700	90-1000		115-1000		115-1000	400-1000	120-600		300-28000	300-28000	nm
Operating Temp	300	300	300	300	300	300	300	300	300	140	300	K

Grazing Incidence Optics:

Future x-ray and far-ultra-violet missions will require large-aperture precision-quality grazing incidence mirrors. The capability required to enable envisioned future missions is truly revolutionary when compared with Chandra optics. The cost cap and mass/volume limitations of grazing optics are profound when compared with normal incidence optics. Doubling the collecting area of a grazing incidence telescope will require as much as a 400X increase in actual mirror surface area. The Constellation-X mission plans a four telescope architecture with 60X the effective collecting aperture as Chandra (6 square meters). Each telescope is planned to be 1.6 meter diameter x 1 meter long with 20X lower areal density (< 3 kg/m2) and 50X lower areal cost (< $ 0.1 M/m2). Efforts are currently underway to develop new materials and new fabrication processes for such challenging optics. Obviously, mass production via some type of replication process is a leading technology candidate. The only mitigating factor is that at 15 arc-second resolution, ConX has 30X looser optical surface figure error requirements than Chandra. But, because of the lower areal density, the mechanical support, alignment and stability of such optics are a significant challenge.

Furthermore, the technical challenges continue to increase for envisioned missions such as the Black Hole Imager (BHI) and the Extreme Universe X-Ray Observatory (EUXO). Through the use of formation flying technology to greatly increase the effective aperture size, BHI plans to achieve a 5000X resolution improvement over Chandra. A summary of grazing incidence X-Ray optics current and future requirements is provided in the tables below.

Table 4.7 Current Grazing Incidence X-Ray Optics Mission Requirements

Capability Metrics	EXOSAT	SSXRT	JET-X	Einstein	ROSAT	Chandra	Astro-E	XMM-Newton	Solar-B	Units
Primary Aperture	0.28	0.40	0.30	0.58	0.83	1.2		0.70		Meters
Segment Diameter	0.28	0.40	0.30	0.58	0.83	1.2		0.70		Meters
Nested Shells	4	118	12	4	4	4		58		
# of Telescopes	1	2	2	1	1	1	5	3		Units
Telescope Mass						1000	60	1260		Kg
Telescope Cost						$250M				$
Mirror Cost						$70M				$
Effective Total Area	0.008	0.14	0.045	0.04	0.1	0.1	.2	.45		m^2
Effective Areal Cost						$700M				$\$/m^2$
Effective Areal Density						10,000	300	2800		kg/m^2
Normal Surface Area						20				m^2
Normal Areal Cost						$3.5M				$\$/m^2$
Normal Areal Density						50		< 20		kg/m^2
Resolution	18	75	20	4	3	0.5	90	15		arc-sec
RMS Surface Fig										Nm
Mech Stability										Hz
Thermal Stability										Nm
Phasing										Nm
Energy Range	?-2	?-12	?-10	0.1-4.5	0.1-2.4	0.1-10		0.1-10		KeV
Operating Temp						300				K

Table 4.8 Future Grazing Incidence X-Ray Optics Mission Requirements

Capability Metrics	Chandra	Astro-E	XMM-Newton	SXI	RAM	ConX Hard	ConX Soft	XEUS	EUXO	BHI	Units
Primary Aperture	1.2		0.70			0.4	1.6		2.5	TBD	meters
Segment Diameter	1.2		0.70				0.4			1 x 0.5	meters
Nested Shells	4		58							TBD	
# of Telescopes	1	5	3			12	4		6	~ 30	units
Telescope Mass	1000	60	1260				2800		18,000		Kg
Telescope Cost	$250M						<$300M				$
Mirror Cost	$70M						<$100M				$
Effective Total Area	0.1	.2	.45				6	10	150		m^2
Effective Areal Cost	$700M						<$20M				$\$/m^2$
Effective Areal Density	10,000	300	2800				450		120		Kg/m^2
Normal Surface Area	20						1000				m^2
Normal Areal Cost	$3.5M						$0.1M				$\$/m^2$
Normal Areal Density	50		< 20				< 3		0.5		Kg/m^2
Resolution	0.5	90	15	10	1	30	15	5	0.1	0.0001	Arc-sec
RMS Surface Fig										3	Nm
Mech Stability											Hz
Thermal Stability											Nm
Phasing											Nm
Energy Range	0.1-10		0.1-10			0.2-1.5	6-60	0.5-30		0.4-7	KeV
Operating Temp	300										K

While this discussion of technology needs for x-ray optics has concentrated on grazing incidence approaches, there is also an on-going need to invest in normal incidence x-ray optics technology. This technology is needed to support a series of smaller scale Sun-Earth science missions that require x-ray optics and which could benefit from incremental quality and cost reduction improvements.

Diffractive, Refractive and Novel Optics:

In addition to the areas discussed in the preceding sections, there is also a need for diffractive, refractive and novel optics that includes coded apertures, occulting imaging, holographic optical elements (HOEs), etc. These classes of novel optics are hard to roadmap because of their early stage of development, but they may enable enhanced (and more affordable) approaches to planned missions as well as unexpected missions through their clever use of novel concepts in optics. This is a critical area to encourage, particularly as the technological challenges increase in difficulty for traditional optics approaches.

Optics Summary:

Assuming that it takes 8 and 12 years to fully mature an optics technology capability from TRL-2 to TRL-6, table 4.9 summarizes the TRL-6 need dates and technology development start dates for each optics capability identified in this section of the Roadmap.

Table 4.9 Timeframe for Technology/Capability Deployment					
Sub-Capability	Mission	Launch	Technology	Need	Start
Precision	TPF-C	2016	4x8 meter Mirror	2010	In-Process
Grazing	ConX	2017	15” x-ray Telescope	2012	In-Process
Cryogenic	TPF-I	2019	4 meter Mirror	2013	2005
Cryogenic	IP	< 2020	Polarization Mirror	2014	2006
Cryogenic	SAFIR	> 2020	Low Cost Mirrors	2015	2006

Precision	LUVO	>2020	Low Cost UVO Mirrors	2015	2006
Cryogenic or Precision	LF	>2025	25 meter Telescope	2020	2010
Grazing	BHI	>2025	Ultra-Low Cost Mirrors	2027	2017
Cryogenic or Precision	PI	>2032	50 meter Telescope	2020	2010
Grazing	EUXO	>2032	0.1 arc-sec X-ray Telescope	2027	2017

4.1.6.2 Wavefront Sensing and Control & Interferometry

Many future missions will require large aperture telescopes to collect faint light from distant and cold sources and to provide high angular resolution to investigate the "fine structure" of the universe. Because of the size of these apertures and the need to make them light enough for launch, their stiffness will be inadequate to passively maintain the high quality wavefront essential to the intended scientific investigations. Active wavefront sensing and control (WFSC) will be needed to compensate for wavefront errors in real-time and on-orbit, and will enable more cost effective telescopes at higher performance levels than rigid, monolithic telescopes such as HST.

For missions requiring angular resolutions unattainable with any practical single aperture, a spatial interferometer may be used to effectively divide a very large aperture telescope into separate smaller, discrete apertures. Extremely high angular resolution is enabled by combining the beams from these smaller aperture telescopes across areas larger than can be covered by a single aperture. For some applications, the separate apertures can be positioned with respect to each other with a common support structure. However, in other cases, the required area is so large that the separate telescopes can no longer be structurally connected, but instead must be flown separately in formation and connected through accurate WFSC to create a large coherent, synthetic aperture. The wavefront sensors must be able to operate on wavefronts that are disjoint and have discontinuities of multiple wavelengths. Imaging interferometers will also require the development of algorithms and software for image formation and restoration.

Both single-aperture telescopes and interferometers require new wavefront sensing and control technology. WFSC is a system-level technology that includes sensing a reference source, signal processing, dynamic computation of parameters to control opto-mechanical devices, and distributed system communication to a mechanical control system. Telescope reference sources include lasers, edge sensors on the optics, or a sufficiently strong source in the field of view.

Ground-based testbeds are essential for developing the ability to sense and control wavefronts under realistic conditions. Several WFSC testbeds were developed for both JWST and SIM, and have been in active use for several years. New missions will require increasingly complex testbeds. Technology is needed to better calculate and emulate the space environment (including zero-g, radiation fields, thermal backgrounds, and space contamination). Fundamental research is needed in algorithm development, high speed digital signal processing, actuator devices, low power devices, long life-time lasers, and advanced sensors.

The first key mission for WFSC technology after JWST is TPF-C, which will need to sense and correct the wavefront to two orders of magnitude greater accuracy than JWST. TPF-C will also need speckle-suppression hardware and software to achieve the required 10^{10} contrast in broadband light. Improved fidelity in vector (polarization) optical modeling is needed to meet the accuracy requirements of high-contrast imaging. LUVO, with its shorter wavelengths, requires five times better WFSC (8 nm rms) than does JWST. The LUVO WFSC needs to operate continuously in an autonomous, closed-loop fashion. Formation-flying systems, such as TPF-I, Stellar Imager, and Life Finder will not be possible without advanced WFSC. For formation-flying systems, the trade-off must be made between wavefront sensing based on the science object versus internal laser metrology versus a formation-flying beacon far in front of the observatory. In addition, low cost 3-meter class telescopes with multiple applications ranging from imaging to coherent collection (laser communications and LIDAR) will require high temporal bandwidth active control. Such low-cost modest-sized apertures will enable more affordable solar, Earth science, and astronomy missions than now possible.

Laser metrology is under development for SIM. Future missions will require lasers to operate over greater distances, with longer in-space lifetimes, and with much more complicated mechanical, power and thermal system architectures. Laser metrology between continuously moving platforms will be necessary for rotating systems.

Wavefront control for TPF-C will require 50 picometer (pm) (λ/10,000) deformable mirrors stable over periods of hours or new architectures based on active control will need to be developed. TPF-C will also require innovative amplitude masks with unprecedented accuracy.

Cryogenic precision motion control is required for infrared systems. Closed-loop intelligent control of the entire system, involving multiple sensors and multiple structures, operating at a variety of temporal bandwidths, will be required. This will necessitate high-speed flight-qualified computers. A variety of hardware approaches, including actuated hybrid mirrors, nanolaminate mirrors, deformable mirrors (including MEMS) and actuators require further development to achieve finer control, larger stroke, more degrees of freedom, and longer life. For each system, a trade-off must be made between the demands on the optical quality of the primary optics versus employment of a smaller deformable mirror farther along the optical chain. Space telescope systems can benefit from the technology being developed for ground-based observatories and directed-energy systems employing adaptive optics, although the differences in mission-specific requirements must be carefully addressed.

Ground-based testbeds are needed to explore system trades, develop and validate algorithms, and validate models. They must be used in continuous iteration between concept development and algorithms/modeling. Flight-like conditions including appropriate cryogenic, vacuum, and low-vibration environments will be necessary. Pathfinders, including flight demonstrators, will be critical to future mission success.

Further innovations, typified by the success of speckle nulling, will be needed to achieve performance goals in a cost-effective fashion. Funding is needed for low-TRL innovative architecture/algorithm testbeds. Funding of a broad range of groups in testbed development is critical for reaching out to the larger community to harvest new approaches to solving these technologically challenging problems.

4.1.6.3 Distributed and Advanced Spacecraft Systems

A Distributed and Advanced Spacecraft System (DASS) is any set of more than one spacecraft whose dynamics are coupled through the introduction of a cooperative sensing and control architecture. A summary of the upcoming ATO missions requiring DASS capabilities is shown in Table 4.10. As can be seen, many longer term missions are enabled by an array, sometimes a large array, of spacecraft of a generally common design flown in formation.

Therefore, a key DASS capability is spacecraft formation flight which enables collective behavior through interaction and cooperation among multiple spaceraft, thus forming a single functional unit that can exhibit a common system wide capability. Of course, the fact that multiple spacecraft must be built is a significant negative aspect of DASS. Replicating all spacecraft sub-systems on each vehicle is expensive. Numerous quantitative trade analyses have shown that under traditional metrics of mass and cost, formation flown systems are not competitive when a mission can be performed using a single spacecraft. Instead, they win on the more esoteric metrics of graceful degradation and reconfigurability. However, it is true that formation flown spacecraft are often identical, and may therefore offer benefits of economy of scale. Further work is needed in the area of reducing development and test costs for replicated spacecraft if formation flown systems can hope to be competitive.

Space Science	SOA	LISA	CON-X	TPF-I	LF	UVOI	BHI	BBO	PI	FISI
Number of S/C	2	3	4	5	4 - 5	20-30	33	12	80 - 100	4
Geometry Maintenance	FF	FF	pointing	FF	FF	FF	FF	FF	FF	tether
Separation control	m	none	none	1 cm			5 um	1 um		
Separation knowledge	cm	<nm	coarse	1 mm			< 1 um	< 1um		
Thrust Range		1-100 uN				1 uN	uN - 0.1 N			
Min Baseline	100 m	5e6 km		75 m	100 m	100 m	1000 km	50000 km	100 km	100 m
Max Baseline	km			200 m	500 m	500 m	10000 km	~1 AU	3000 km	1000 m
Pointing Control				20 asec		10 uas	10-100 nas			
Mission Lifetime	5 yrs	10 yrs	5 yrs	5 yrs	> 5 yrs	> 10 yrs			5-20+ yrs	
Orbit	LEO	Helio	SE L2	SE L2	SE L2	SE L2		Helio	SE L2	SE L2
Launch Date		2005-2015	2015-2025	2015-2025	2025+	2025+	2025+	2025+	2025+	2025+

Table 4.10 Key Distributed and Advanced Spacecraft System Need Summary

The expense and comlexity of ground operations for each spacecraft of a multi-element formation creates a need for more autonomous operations. For example, having multiple spacecraft in close proximity undergoing comparatively rapid maneuvers dramatically changes the nature of safe modes: a faulty spacecraft must also ensure that it will not collide with others in addition to safing its own systems and operations. Furthermore, during nominal operation, it must plan its maneuvers such that if it does experience a fault, the likelihood of collision is remote. Fault detection, isolation, and recovery (FDIR) is more complex and requires a vigilant on-board software watchdog that reacts to both intra- as well as inter-spacecraft faults and plans according to the consequences. During nominal operations, system synchronization, inter-vehicle metrology and staged control (coarse-fine precision), on-line maneuver path planning subject to constraints (collision, plume impingement, thermal, stray light), and high bandwidth communication are challenges.

Current concepts for formation flown systems rely upon the use of propellant to maneuver and maintain the formation, thereby limiting mission lifetime and contaminating the environment (deposition on optical surfaces, plume impingement, thermal emission). Propellant-less formation flight should be investigated, to include consideration of the use of natural orbits, natural fields (magnetic, solar pressure), and potential fields generated by the spacecraft themselves (electro-magnetic, electro-static).

In another approach, tethers have several promising features. First, they can be used to maintain and alter the orientation of spacecraft distributed across large baselines. Unlike formation flight, sub-system services (e.g., power) can be transmitted through the tether thereby reducing the need to replicate all sub-systems on each spacecraft. The challenges of tethers include controlling high frequency, nonlinear, and sometimes unstable dynamics.

Roughly three quarters of the proposed far term space science missions baseline distributed, formation flown architectures. Yet, no mission has flown which exhibits the duration, precision, autonomy, reconfigurability, or number of spacecraft needed for these missions. Several on-orbit technology demonstrations have begun development, but all were cancelled prior to flight. Due to the numerous low TRL capabilities that need to be matured, it may not make sense to demonstrate them all on one precursor mission (risk) or to mature them individually through a sequence of independent free-fliers (cost). DASS would benefit from a reconfigurable test platform where technology “layers” can mature in a spiral development, first maturing algorithms in a risk-tolerant setting and then maturing spacecraft sub-systems including propulsion, sensing, and communications. Finally, payload technologies including collectors, combiners and optical control could be added and tested. As an additional benefit, spiral testing promotes the development of a modular and extensible architecture which would be more broadly beneficial (e.g., supporting the development of capabilities for assembly, servicing, and spacecraft upgrades). The International Space Station (ISS) may provide an opportunity for an early spiral development of these capabilities. Servicing flights would bring new technology layers that attach to the DASS vehicles which then deploy from ISS for testing. Access is already available to existing infrastructure such as power, data (up)downlink, and crew for maintenance and upgrade when operating in both the internal (Destiny Lab) and external test environments.

DASS holds the promise to revolutionize space-based advanced telescopes and observatories. By extending the modularity inherent in sparse aperture optical systems to the supporting spacecraft, new operational modalities emerge. Formation flight of optical sub-apertures enables angular resolution far beyond that which is attainable with structurally connected arrays, the tuning of the point spread function to the object being observed, and the synthesis (through maneuvers) of images that would otherwise require prohibitively large filled apertures. However, the benefits go far beyond the synthesized aperture. DASS enables reconfiguration of the array in the event of spacecraft failure and the ability to add new spacecraft to the formation since only soft interfaces need to be established (communications, sensing, control). With a rendezvous and docking capability, cryostats can be replenished, spacecraft can be refueled, and detectors can be upgraded. High packaging efficiency during launch can be achieved through the use of modular components that are deployed or robotically assembled on orbit. Optical and formation flight control provide access to real-time data and code for self-diagnosis, fault detection, and software reconfiguration. Replicated sub-aperture and spacecraft modules can be used by multiple missions thereby increasing production volume and associated savings. As with any revolution, change comes at a price. A coherent roadmap is needed for maturing these technologies in a methodical and incremental manner if the promise of Distributed and Advanced Spacecraft Systems is to become a reality.

4.1.6.4 Cryogenic and Thermal Control Systems

Cryogenic and thermal control systems include both passive and active technologies used to cool large optical systems. The state-of-the-art in this area is the sunshade and thermal isolation being employed to passively cool JWST. Heat switches, advanced radiators, heat pipes, and capillary pump loops are all technologies which need to be further improved in efficiency, size, and cost to better enable high- and low-temperature cooling applications. Cooling technology for telescopes also greatly overlaps with the cooling needs of scientific sensors, and is therefore also addressed in the scientific sensors capability roadmap.

The value of a telescope cooling architecture that includes passive and actively cooled mirrors is vividly illustrated in Figure 4.5 (or 4.6 depending upon how you count) below, showing how mirror temperature reduction produces a lower background that increases the sensitivity and is equivalent to increasing the size of the aperture in the infrared. Specifically, SAFIR's sensitivity improves two orders of magnitude in the far infrared if the temperature of the telescope optics can be lowered from the current ~30K achievable via passive cooling alone to a 4K telescope temperature achievable with the addition of active cooling.

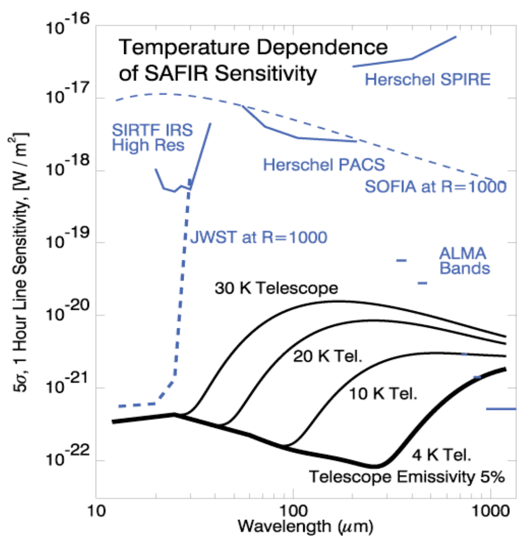


Figure 4.5 – Temperature Dependence of SAFIR Sensitivity

The aspects of passive and active cooling and thermal isolation need to be addressed as a system to meet the challenging goals of future cryogenic missions. Some examples of areas that need to be addressed within each of these three aspects follow.

Passive Cooling:

Passive cooling to a range of 30-80 Kelvin (or lower) is a key aspect of any systems approach to cooling of large optics and structures as it provides the starting point for any additional active cooling needs. For some missions, this may be all that is needed and is within the grasp of programs such as JWST (expected to reach ~35K passively over a 6.4 meter aperture). This is a substantial advance over the recent successful Spitzer telescope which achieved this temperature level in a 0.8 meter aperture. For others, this only provides a more reasonable starting point to allow further active cooling to much lower temperatures. The purposes include:

Reducing the thermal background on sensors
Pre-cooling optical benches
Pre-cooling optics that are actively cooled to lower temperatures (as mentioned)

The technology areas that can help in this include sunshade improvements (more layers, greater distance, better materials), efficient radiators at cool temperatures, efficient heating/cooling distribution, materials for use elsewhere with good thermal properties at low temperature, and coatings and good system concepts employing a combination of passive methods. To ease active cooling loads for very cold systems, a goal to reach ~15K is thought to be an important step, to be traded with the difficulty of obtaining good, efficient active systems.

For the particular case of interferometer missions operating in the thermal IR and longer wavelengths, special shields need to be developed to protect the interferometer beam combination path in addition to the single observing path of a more conventional telescope.

Active Cooling:

Active cooling is required to push the optics and structures below the temperature limits of radiators and passive methods without the life and mission limiting cryogen expendables used for smaller systems and instruments today. In addition to bringing the temperature of the cryogenic optics down to ~4K from the passive limits discussed, active telescope cooling systems will also provide pre-cooling for the scientific sensors that need single digit milli-Kelvin temperatures to achieve the full scientific potential of missions such as SAFIR and others.

Currently, there are multiple coolers that are in development by the DoD and NASA to providing cooling to the 50-80K range. The NASA ACTDP program had a goal of 6K/18K coolers at a TRL7 level in FY07, though this program has been modified and is being applied to JWST for an instrument need. The Plank sorption cooler is an 18-20K system set for launch in FY07. The corresponding electronics that systems need to operate below 30K are at a very early level of development.

There is a significant technology gap between this recent progress and the technology required to produce the 4 Kelvin levels needed to cool larger telescopes and their associated optics. There is a need to extend the ACTDP or comparable technologies to support missions such as SAFIR and potentially TPF-I. In addition to the cooling capacity at low temperatures, these produce little to no vibration so that they may be used to support coronagraphs. A demonstration in space in the ~FY08 timeframe would be useful and a goal of cooler system operation at the 4-5K level and 0.1 W load should be demonstrated to TRL 5 by FY14.

Thermal Isolation:

Even with good passive and active methods, all systems will have warm areas and cold, making the interface between such areas equally important to maintaining the low temperature optics and structures in an efficient manner. Work is required to reduce the heat flow across these interfaces, providing heat switches that allow easier launch conditions (such as on Spitzer, but at a larger scale) and possible redundant cooler operation. A goal of reducing heat switch conductance to ~0.1 W/K @ 6 Kelvin is suggested for development by the FY08 time frame.

4.1.6.5 <u>Large Precision Structures for Observatories</u>

Developing the capability to produce large precision structures for future large observatories is an enabling technology for the majority of space and Earth science missions, for which aperture size is a critical factor. Increased aperture size creates greater sensitivity and greater resolution across the entire electromagnetic spectrum. The James Webb Space Telescope (JWST) already exceeds the volume capability of current launch vehicles: it must therefore be launched folded into the launch vehicle fairing and deployed (optics and structure) on orbit.

Strongly coupled to the size of the structure is the required stability. This stability requirement ranges from nanometers to picometers for interferometers and coronagraphs to microns to nanometers for the very large (many tens of meters) radar systems. While the specific needs/requirements for large precision structures vary with application, there is a common set of high-level areas of investment that span all applications. Hence, this sub-capability is divided into three areas:

- Structure Stability and Precision
- Materials Properties
- Implementation Technology

All three areas are strongly interconnected and must be approached with a long-term, system level investment strategy. For example, materials creep and precision thermal performance in a space environment are fundamental factors in any stability model, but appropriate environmental material properties (particularly at very low temperatures) have never been measured for a wide range of potentially useful materials. A broad understanding of materials properties will be needed to develop cost effective/acceptable risk stable structures. Similarly, issues with regard to implementation technology (e.g., launch load reduction systems and deployment versus assembly versus inflatabilty) factor strongly into design architectures. A comprehensive set of system-level trade studies comparing and quantifying the advantages is needed to guide investment strategies on a case-by-case basis.

Large precision structures represent a capability being developed for the first time with JWST. Future mission studies are developing mission requirements for size, low mass, and stability that greatly exceed those of JWST. If these future telescope/observatory missions are to be realized we must have the capability to develop larger precision structures. This requires development of new materials with high stiffness/mass ratios, good thermal conductivity and good damping characteristics. Nanotechnologies offer some promising possibilities that should be pursued in this area.

Associated with the need for better materials and structures is the need for metrology systems to measure key performance parameters like CTE, creep, stability and damping. Several new technologies have been developed for JWST and are geared for the size and temperature range of that system. Future structural systems will also need to support 4K systems and with increased accuracy for X-ray, LISA and TPFC type applications. This includes pushing the precision of electronics speckle interferometery systems, lower temperature and/or higher accuracy creep and CTE systems. Many of these systems are used as part of the manufacturing process so they must work quickly and cost-effectively.

4.1.6.6 Infrastructure

Infrastructure (both ground and space) has been identified as an ATO sub-capability because of the critical role it plays in enabling cost-effective missions. The ATO Committee addressed three key areas of the infrastructure:

- Workforce
- Integration and Test Facilities
- In-space Operations and Servicing

Workforce:

The development of advanced optical systems in space for NASA, as well defense applications, requires workers with specialized training and experience. We are already exceeding the current national capability for training such people, yet we are hoping to build more sophisticated systems. We must anticipate the need and act to avoid a critical shortage of trained workers in the following areas:

- Optical engineers capable of working on interdisciplinary problems that involve coupling between optical, mechanical, thermal, and manufacturing issues.
- Technicians who develop and execute test and alignment procedures.
- Manufacturing engineers for precision optics.

- Experts in computer and integrated modeling that understand practical issues for complex systems.

A solution to the workforce shortage could involve improvement in both education (schools and universities) and training (experience and apprenticeships). NASA can enable these improvements by providing input and funding to educational institutes and by facilitating intern-type experiences at NASA centers and contractor facilities. NASA can also improve on some of the workforce issues with better planning and management that respects the trained workforce as a resource. Government funded projects come and go, typically with little coordination. This leads to a shortage of technical expertise at times when multiple projects are underway. As industry, academia, and the free market accommodate and fill the empty jobs, the situation may reverse. The contractors respond by laying off employees, which drives many bright people away from aerospace industry entirely.

Integration and Testing:

New facilities for thermal vacuum testing need to be considered to execute this roadmap. Large thermal vacuum test facilities have historically been a major cost and schedule consideration for large space telescopes. These issues will clearly be even more challenging for future 10-meter class space telescopes. In the past, individual missions have been responsible for modifications to existing facilities or acquisition of new facilities even though these often benefit multiple missions. Next generation NASA missions, such as TPFC, Con-X, and SAFIR, will likely build upon the test heritage and lessons learned from JWST but will have new and unique test facility requirements. Therefore, NASA needs to decide whether leveraging off the JWST facility or other existing facilities makes sense or whether a new facility that can more cost-effectively accommodate these and other missions makes sense. If a new facility is developed, it will be required to maximize flexibility in the cryo thermal system, the cryo distribution system, optical metrology penetration, access ports for payload installation, and vibration isolation systems to accommodate future programs. The team building the facility will need expertise in cryogenics, vibration isolation methods, contamination, and optical testing to ensure success of the testing but also to minimize the overall cost to the programs. Finally, the facility location needs to factor in the teams planning on using it, the transportation of payloads to and from the facility, and program schedule impacts. As plans for the future test facility needs mature, NASA should work with other government agencies through the Large Optics Working Group of the Space Technology Alliance to ensure that other agency interests are considered as this facility may have other uses.

Developing the infrastructure for very large, future systems will require currently unplanned (and un-costed) test and analysis of existing programs. Larger optical systems that rely on in-space assembly will use analysis and test techniques developed and verified on current programs such as JWST. It is essential to verify that subsystem analysis tools provide adequate insight into the end-item performance parameters. Additional telemetry from near term systems may also be required to verify analytical models such that future on-orbit assembly systems will operate as predicted. By starting to build the analytical tools soon and combining these tools with a robust verification plan during traditional integration and test, a high level of confidence can be provided when development of on-orbit assembly and test programs commence. If these tools are not developed early, critical failures could occur that would impact both NASA and the contractor's ability to execute this new class of program in a cost effective manner.

In-Space Observatory Support/Servicing:

Low-earth orbit servicing of telescopes has been demonstrated with space shuttle servicing of the Hubble Space Telescope. This servicing was critical to fixing the spherical aberration in the primary mirror as well as fixing a number of other problems that would have been debilitating to the mission. In addition, each servicing mission substituted new instruments with new capabilities that were the functional equivalent of a new mission. This servicing approach is similar to ground telescopes where an observatory can be continually upgraded with modern instrumentation. With the preponderance of future large observatories going to L2, the servicing approach used for HST will not be possible. While servicing and assembly at L2 is possible, the key challenge is whether it can be done in a cost-effective manner. For this reason, the ATO team recommends further studies of opportunities to leverage the Exploration program to make in-space servicing and/or assembly cost-effective. For example, Exploration may need multiple launches to the moon which could carry upgrade equipment to the Earth-moon L1 Lagrange point which provides low energy transfer to sun-earth L2.

In addition to studying how the Exploration program could be leveraged, the ATO Committee also evaluated strategic plans to determine which missions were timed to be possible candidates for servicing or assembly. It appears that SAFIR offers the first logical opportunity for servicing both because of a relatively low maturity architecture that could be made serviceable and because the FIR is still an area with relatively modest capability detectors (array size and sensitivity) that could benefit from upgrades. We also concluded that a logical assembly opportunity would be the Life Finder mission because of the need for extremely large apertures that would be complicated to deploy. However, other long-term missions are also candidates for servicing and assembly but the decision needs to be made early in the architecture development so that it can be accommodated without significant changes to the cost of the program.

4.2 Roadmap Development

4.2.1 Legacy Activities and Roadmap Assumptions

This roadmap traces directly back to the statement in the President's *Vision for Space Exploration* to:

- Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars.

It is fully consistent with the Aldridge Report which stated:

- The Commission finds implementing the space exploration vision will be enabled by scientific knowledge, and will enable compelling scientific opportunities to study Earth and its environs, the solar system, other planetary systems and the universe.

Finally, the roadmap draws much of its strategic guidance from NASA's Direction for 2005 and Beyond (budget supplement) and the most recent National Academy of Sciences Astronomy and Astrophysics Decadal Survey.

The ATO Roadmap assumed for planning purposes the list of missions and launch dates provided by APIO and verified through dialog with Strategic Roadmap panels. A summary of the assumed missions is provided on the roadmap timelines in the figures above. JWST and SIM were included on the timelines for reference and are not part of the roadmap as they are currently in Phase B development. Mission technology needs were based on NASA heritage roadmaps and presentation and reference material provided to the ATO committee from mission representatives. In addition, a number of more specific assumptions concerning the scope of this roadmap were closely coordinated with other roadmaps, particularly the Scientific Instruments and Sensors Capability Roadmap. Specifically:

- The Scientific Instruments and Sensors roadmap was assumed to treat heat pipe cooling to radiators, optical bench cooling, detector cooling, instrument optics, microwave system electronics and antennas/waveguides, and laser systems.
- The modeling roadmap committee was assumed to cover modeling and integrated modeling tools.

In addition to this coordination with other roadmaps, an assumption was made regarding the fact that the Explorer and Discovery programs were not called out in the roadmap and were only covered as part of the general need for low cost 3-meter class telescopes and associated technologies that could enable these types of missions.